# GROSS-SHELL EFFECTS IN THE DISSIPATIVE NUCLEAR DYNAMICS

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# Plan of talk

**1. INTRODUCTION. Order and Chaos: Quantum-classical correspondence in the non-linear collective dynamics**

**2. QUANTUM DYNAMICS**

**3. NUMERICAL RESULTS**

**3a. THE S.P. SPECTRA**

**3b. EXCITATION ENERGIES AND SHELL EFFECTS**

**4. SEMICLASSICAL ONE-BODY FRICTION**

**5. CONCLUSIONS**

**1) WALL FORMULA**, Swiatecki et al. (1977,78)

**2) CLASSICAL $\Longleftrightarrow$ QUANTUM COLLECTIVE DYNAMICS, NON-ADIABATIC NON-LINEAR CORRECTIONS, ORDER vs CHAOS, POINCARE SECTIONS AND LYAPUNOV EXPONENTS,** Swiatecki, Blocki, Skalski et al. (1995-1999)

**4) QUANTUM AND CLASSICAL RESULTS FOR EXCITATION ENERGY,** Swiatecki, Blocki, Skalski, Magierski et al. (1995-2007); Blocki, Yatsyshyn, Magner (2010,2011) **FOR 10-20 PERIODS OF OSCILLATIONS**

**5) SEMICLASSICAL ONE-BODY FRICTION AT SLOW AND SMALL-AMPLITUDE VIBRATIONS,** Koonin& Randrup (1977,78); **Gutzwiller POT:** Gzhebinsky, Magner, Fedotkin (2007), **SMOOTH LOCAL FRICTION** (WALL FORMULA)

**6) QUANTUM AND SEMICLASSICAL ONE-BODY FRICTION AND SHELL EFFECTS**

# 3. QUANTUM DYNAMICS

$$i\hbar\frac{\partial}{\partial t}\psi = \mathcal{H}(t)\psi, \qquad \mathcal{H}(t) = \hat{T} + V(r,t)$$

$$V(r,\theta,t) = -\frac{V_0}{1+\exp\{[r-R(\theta,t)]/a\}}$$

$$R(\theta,t) = R_0\left[1+\alpha_n(t)P_n(\cos\theta)+\alpha_1(t)P_1(\cos\theta)\right]/\lambda(t),$$

$$\alpha_n(t) = \alpha_{st} + \alpha_n^0\cos(\omega t), \qquad \alpha_n^0 = \alpha\sqrt{(2n+1)/5}$$

$$\psi(t) = \sum_i C_i(t)\phi_i, \quad \Rightarrow \quad < dE/dt >= \gamma\omega^2\alpha^2/2,$$

**WALL FORMULA:** $\frac{dE}{dt} = \rho\bar{v}\oint \dot{n}^2 d\sigma = 9mv_F^2\eta\alpha\omega A/40$

$$\frac{\Delta E_{wf}}{E_0} \propto \left(\tau + \frac{1}{5}\tau^2\right), \qquad \tau = \frac{3}{4}\alpha\eta\left[\omega t - \frac{1}{2}sin(2\omega t)\right]$$

**ADIABATICITY PARAMETER:**

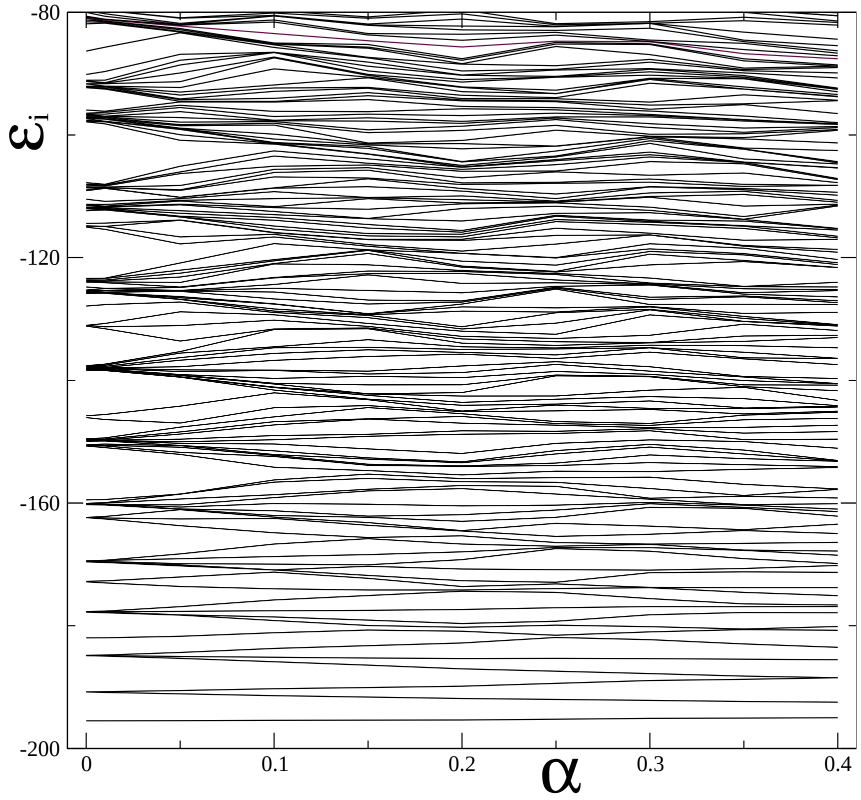
$$\eta = \alpha\frac{\omega}{\Omega}, \qquad \Omega = \frac{v_F}{R_0}$$

# 3. NUMERICAL RESULTS

$$H\phi_i = \varepsilon_i \phi_i, \quad V(r,\theta) = -V_0 \left[1 + \exp\left\{\left[r - R(\theta)\right]/a\right\}\right]^{-1}$$

$$R(\theta) = R_0 \left[1 + \alpha_n P_n(\cos\theta) + \alpha_1 P_1(\cos\theta)\right]/\lambda, \quad \alpha_n = \alpha\sqrt{(2n+1)/5}$$

$P_2$




$P_3$

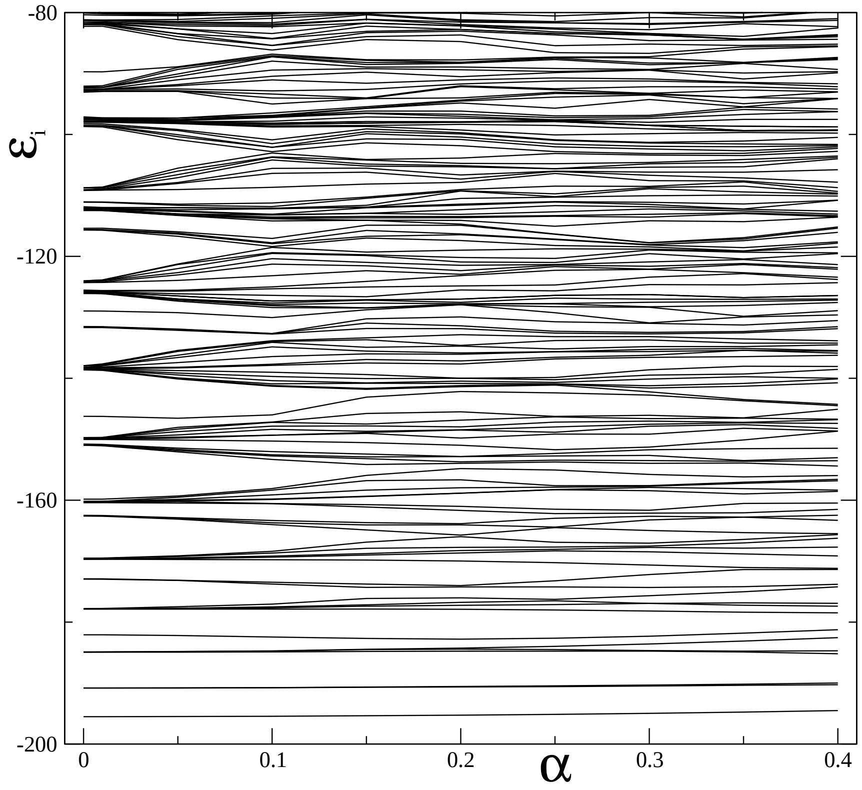



**Fig. 1b.** The s.p. energy levels $\varepsilon_i$ in the WS potential ($V_0 = 200$ MeV, $R = 6.622$ fm, $a = 0.1$ fm) as function of the deformation $\alpha$

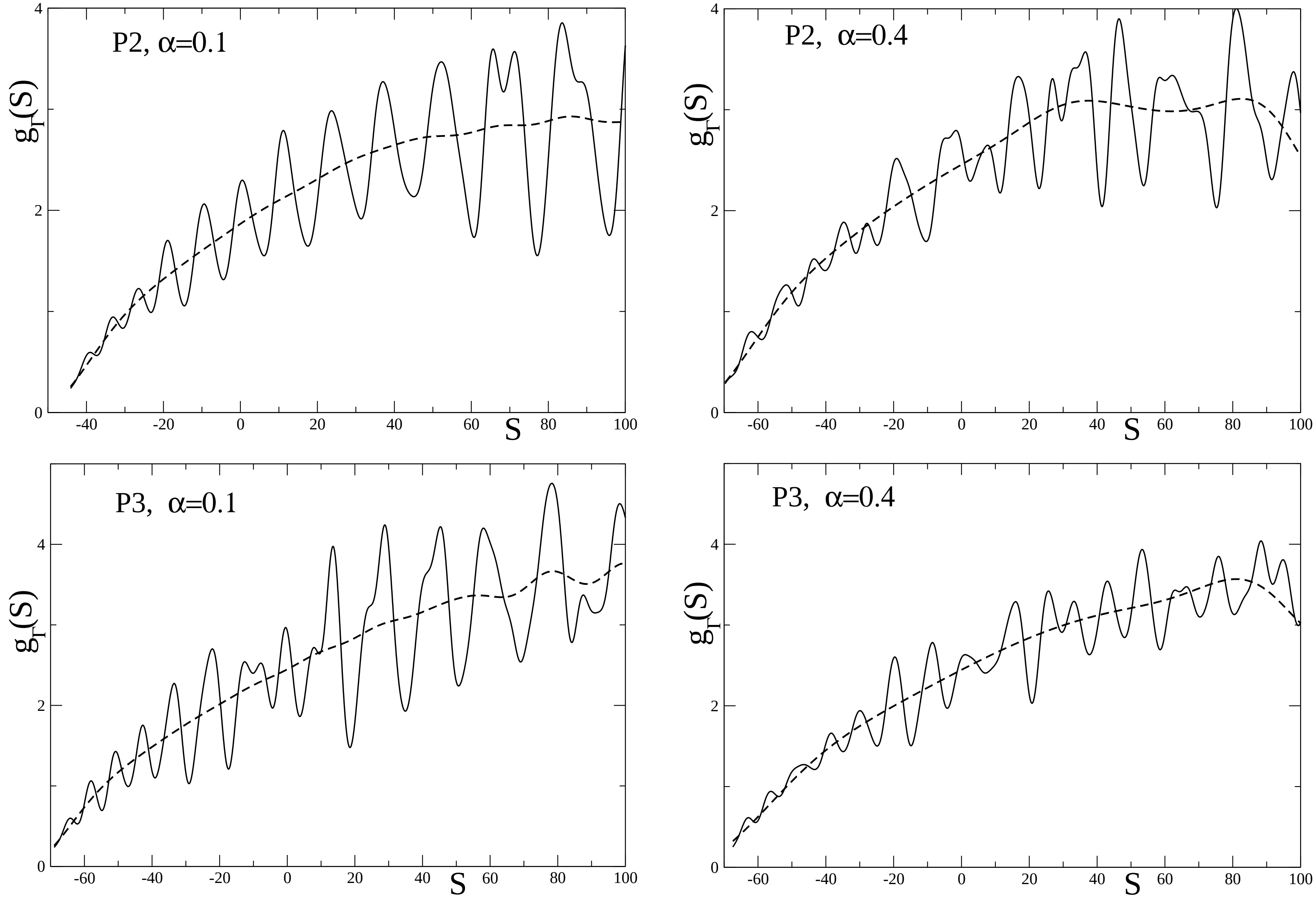



**Fig. 2. Level densities $g_\Gamma(S)$ as function of energy $S$; dashed is smooth density $\tilde{g}(S)$; solid is the total density $g_\Gamma(S)$ ($\Gamma = 3$ MeV).**

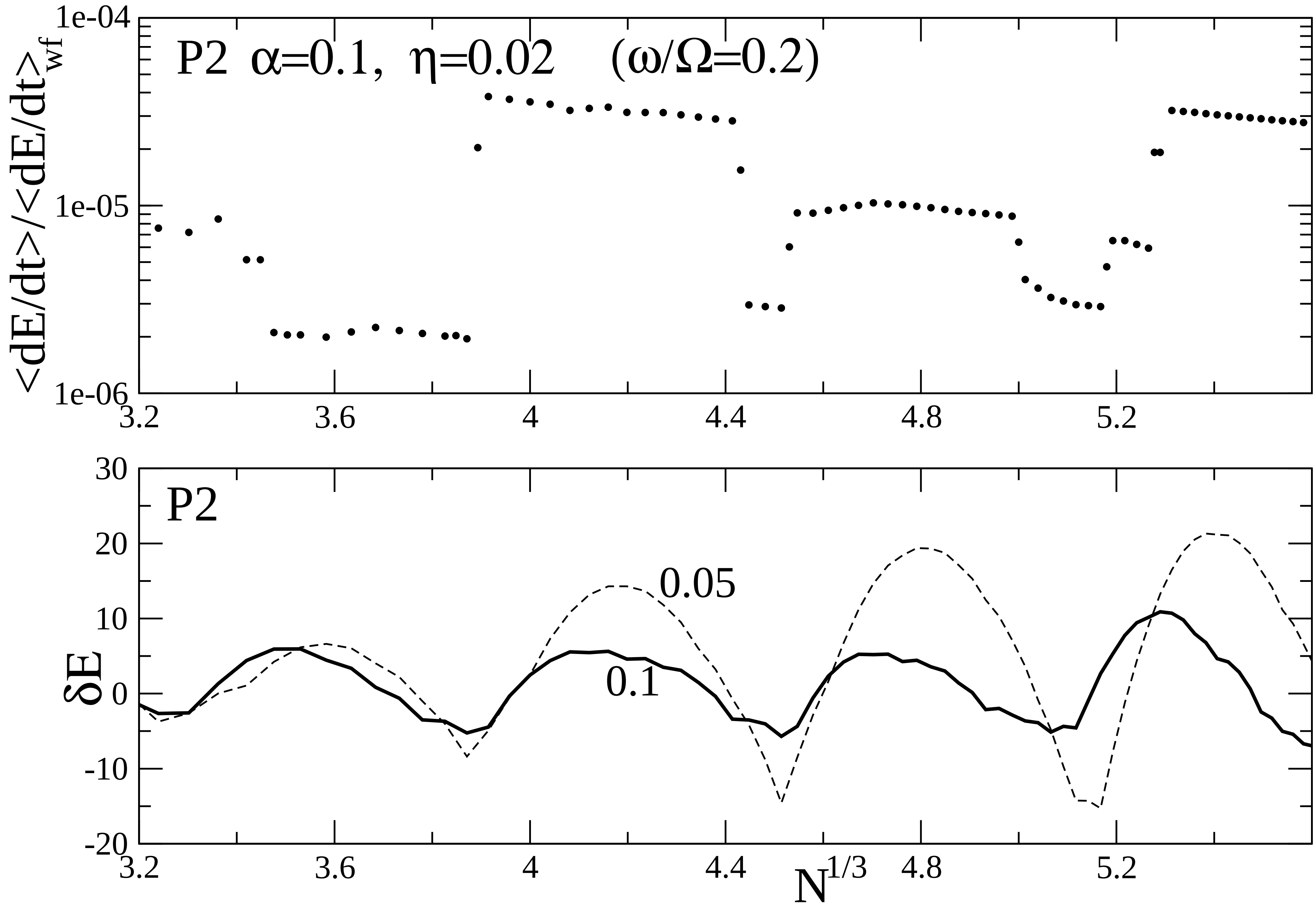



**Fig. 10.** Mean time derivatives $< dE/dt >$ in the w.f. units (top) and shell corrections $\delta E$ (bottom) vs. particle numbers, $N^{1/3}$.

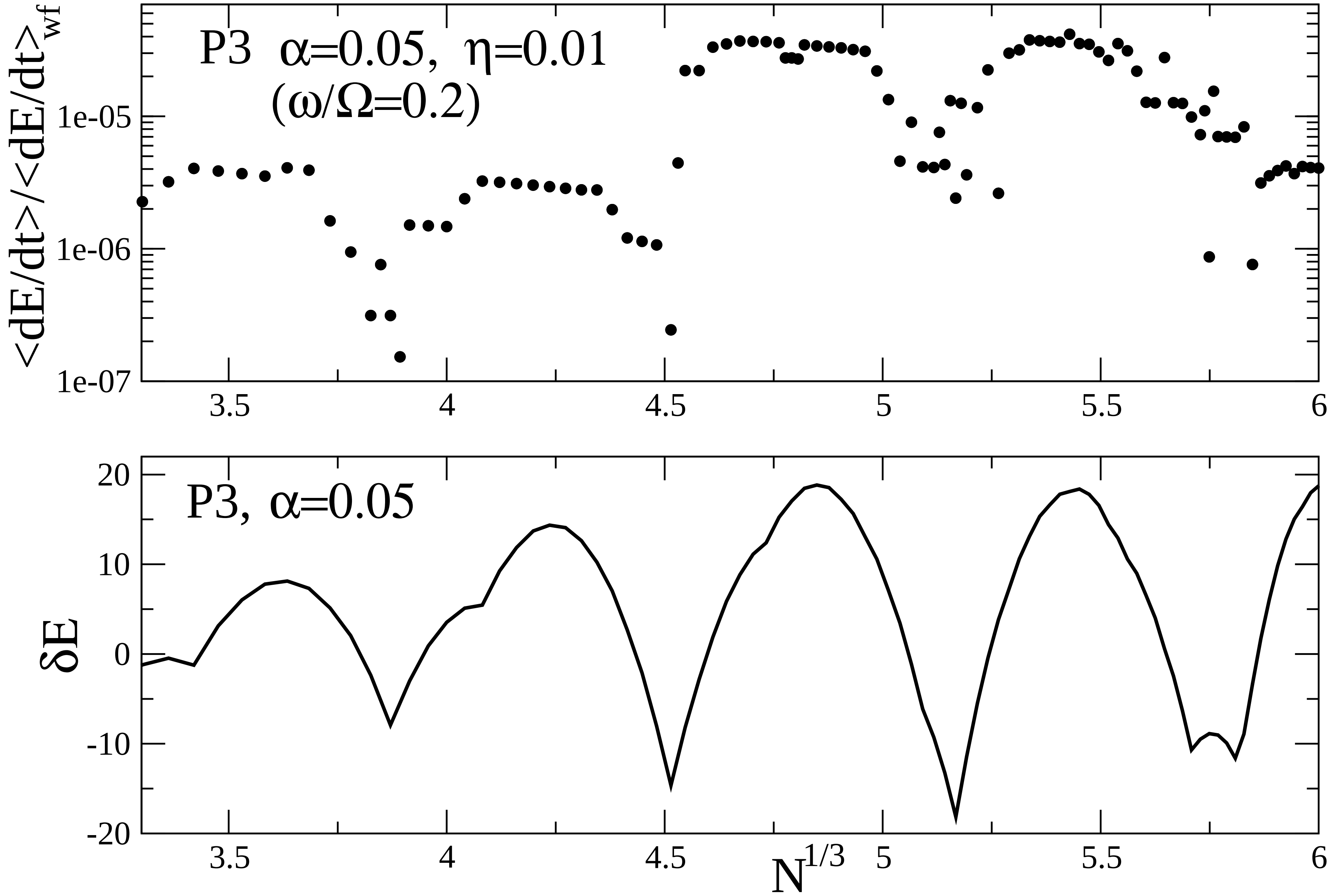



**Fig. 11.** **Mean time derivatives $< dE/dt >$ in the w.f. units (top) and shell corrections $\delta E$ (bottom) vs. particle numbers, $N^{1/3}$.**

# 4. SEMICLASSICAL ONE-BODY FRICTION (sph. box)

$$\gamma = \int_0^\pi \mathrm{d}\psi \, \sin\psi \, P_n(\cos\psi) \, \gamma(\psi), \qquad \gamma(\psi) = \left(\partial^2 \mathrm{Im} G / \partial r_1 \partial r_2\right)^2_{S,F}$$

**GREEN'S FUNCTION (Gutzwiller, 1971) for $k_F R_0 \sim A^{1/3} >> 1$:**

$$G(\mathbf{r}_1, \mathbf{r}_2; \varepsilon) = \sum_{CT} \mathcal{A}_{CT}(\mathbf{r}_1, \mathbf{r}_2; \varepsilon) \exp\left[\frac{i}{\hbar} S_{CT}(\mathbf{r}_1, \mathbf{r}_2; \varepsilon) - \frac{i\pi}{2}\mu_{CT} - \phi_d\right]$$

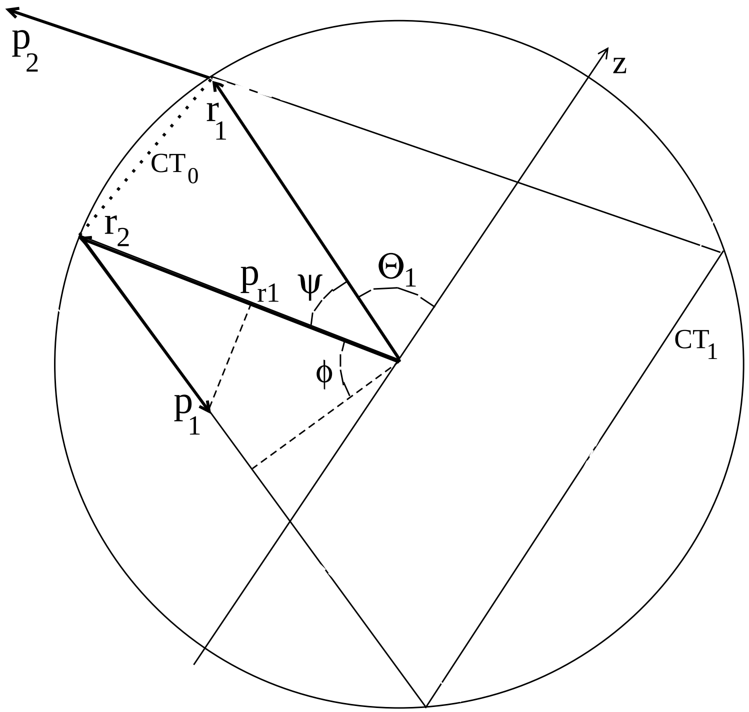



**Fig. 4. The trajectories $CT_0$ and $CT_1$**

$$\mathbf{r}_1\{r_1, \theta_1, \varphi_1\} \Rightarrow \mathbf{r}_2\{r_2, \theta_2, \varphi_2\}$$

CT: $\phi = \phi_{PO} - \frac{\psi}{2v}, \quad \phi_{PO} = \frac{\pi w}{v}$

$v$ is the vertex number and $w$ is the winding number,

$$\psi = \theta_2 - \theta_1, \quad p(\mathbf{r}) = \sqrt{2m\left[\varepsilon - V(\mathbf{r})\right]}$$

$$G = G_{CT_0} + G_{CT_1}$$

$$G_{CT_0} \approx -\frac{m}{2\pi\hbar^2 r_{12}} \exp\left[\frac{i}{\hbar} r_{12} p(\mathbf{r})\right], \quad G_1 = \sum_{CT \neq CT_0} G_{CT}$$

**SMOOTH FRICTION:** $\gamma(\psi) = \gamma_{wf}(\psi) + \gamma_{corr}(\psi)$,

$$\gamma_{wf}(\psi) = (2n+1)\gamma_{wf}\ \delta(\psi)/4\pi^2 \sin\psi, \qquad \gamma_{wf} = d_s\hbar(k_F R)^4/10\pi,$$

$$\frac{\gamma_{corr}(\psi)}{\gamma_{wf}} = \sum_{v,w} \frac{\sin^3\phi \cos\phi}{v \sin\psi}\left[1 - \exp\left(-\frac{\sin\psi}{\Delta}\right)\right]$$

$$\Delta = \frac{8\pi}{k_F R_0 \cos\phi_{PO}}, \quad \phi = \phi_{PO} - \frac{\psi}{2v}, \quad \phi_{PO} = \frac{\pi w}{v}$$

| $n$ | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| BYM | 1.049 | 0.944 | 1.002 | 0.991 | 1.000 | 0.997 | 1.000 | 0.999 |
| KR | 0.00 | 0.85 | 0.45 | 0.90 | 0.62 | 0.93 | 0.71 | 0.94 |

Table: Friction coefficients $\gamma/\gamma_{wf}$ vs multipolarity $n$ for small slow vibrations, $k_F R_0 = 10$; KR is Koonin & Randrup's results, 1977.

$$\delta E = \sum_{PO}\left(\frac{\hbar}{t_{PO}}\right)^2 \mathcal{B}_{PO} \cos\left[\frac{1}{\hbar}S_{PO}(\varepsilon_F) - \frac{\pi}{2}\mu_{PO}\right],$$ (Strutinsky & M.,1975,76)

$$\delta\gamma = (2n+1)^{-1}\sum_{PO,PO'} \Upsilon_{PO} \cos\left\{\frac{1}{\hbar}\left[S_{PO}(\varepsilon_F) \pm S_{PO'}(\varepsilon_F)\right]\right\}, \quad \hbar\Omega = 2\pi\hbar/t_{PO}$$

# CONCLUSIONS

- **The excitation energies of the quantum gas in the Woods-Saxon potential with sharp surfaces rippled according to the Legendre polynomials $P_2$ and $P_3$ are obtained for a slow and small-amplitude collective motion.**
- **We found relatively strong correlations between one-body friction coefficients and shell-correction energies as functions of the particle number for slow small-amplitude vibrations**
- **We derived semiclassically within the POT the smooth one-body friction coefficients for slow small-amplitude vibrations near the spherical shape.**
- **As perspectives, our quantum and semiclassical results might be helpful for better understanding the one-body friction within the Microscopic-Macroscopic Model for nuclear fission and heavy ion collisions**

**THANKS!**